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## Nuclear thermodynamics with isospin degree of freedom: From first results to future possibilities with A and Z identification arrays

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**Summary.** — Nuclear thermodynamics studies evidenced the existence of a first-order phase transition, namely of the liquid-gas type, without paying attention to the isospin degree of freedom. On the other hand, only few results with the introduction of the isospin variable have been so far obtained. Moreover above all a key question remains. It concerns the origin of the dynamics of the phase transition: spinodal instabilities or not with possible consequences and new signatures related to the introduction of the isospin variable.

### 1. — Introduction

During the last decades nuclear thermodynamics was widely studied through heavy-ion collisions at intermediate and relativistic energies and through hadron-nucleus collisions. With such collisions, depending on impact parameter, a nucleus (or a nuclear system) can be heated, compressed, diluted. These systems are expected to undergo a liquid-gas-type phase transition that manifests through nuclear multifragmentation. This theoretical expectation is due to the similarity between the nuclear interaction and the Van der Waals forces acting in classical fluids [1]. However a nucleus (or a nuclear system) is a finite system which shows specific behaviours in the transition region. Most of the predicted specific signals were experimentally evidenced without paying attention to the isospin degree of freedom. Some are a direct consequence of the abnormal curvature of the entropy in the coexistence region which is no more additive due to surface (finite-size) effects [1,2]. The answer of a key point is still pending, it concerns the dynamics of the transition. And the question is: is the phase separation produced by spinodal instabilities or produced at equilibrium? At present there is an indication that multifragmentation may be induced by spinodal instabilities but the confidence level of the fossil signature is not sufficient (3–4  $\sigma$ ) [3,4]. Such instabilities may happen when the system evolves through the mechanically unstable spinodal region of the phase diagram, located

at densities  $\rho \leq \rho_0$  and temperature below the critical temperature. Such conditions are well explored in central and mid-peripheral nuclear collisions around the Fermi energy. If spinodal instabilities can be experimentally confirmed, new signatures are theoretically predicted in relation with the introduction of the isospin degree of freedom [5-7], which can be experimentally studied.

In this paper, after a brief review of the nuclear phase transition signals without paying attention to isospin, we shall discuss first experimental results showing the influence of the isospin degree of freedom. Then the key question of the dynamics of the transition and the related signatures in relation with isospin will be discussed.

## 2. – Direct signatures of first-order phase transition in finite nuclear systems

For finite systems the entropy per particle at equilibrium  $S(E)/A$  in the coexistence region shows a convexity because the entropy of surfaces which separate the two phases does not scale with  $A$ . This behaviour induces specific direct signatures of the phase transition. Entropy convexity is necessarily accompanied by a negative heat capacity in the coexistence zone. This direct signature was early observed (with a microcanonical sampling) for 35A MeV Au+Au semi-peripheral collisions [8] and confirmed by the INDRA Collaboration for 32–50A MeV Xe+Sn central collisions [9]. More recently another direct signature associated to convexity was observed: the bimodal distribution of an order parameter like the charge of the largest fragment ( $Z_{max}$ ) of the multifragmentation partitions. Bimodality was observed (with a canonical sampling) in 60–100A MeV Au+Au semi-peripheral collisions, allowing moreover to estimate the latent heat for nuclei close to gold around 8 MeV and to set the appearance of the pure gas phase above 8.5–10.4 MeV [10].

For caloric curves their shape depends on the path followed by the system in the microcanonical equation of state surface, and a backbending (direct signature) can only

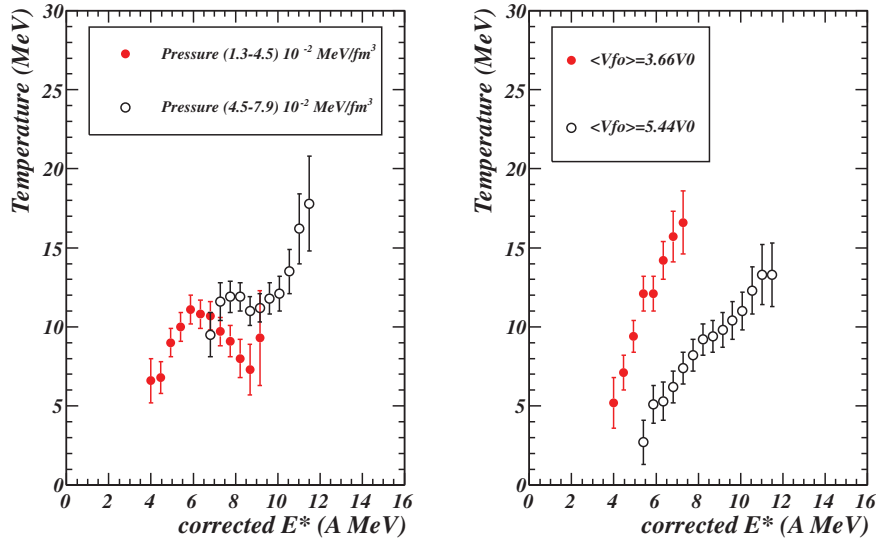


Fig. 1. – Caloric curves for selected ranges of pressure (left) and constrained at average volumes (right). Error bars include statistical and systematic errors. From [14].

be observed for a transition at constant pressure [11]. This was evidenced very recently for central 32–50  $A$  MeV Xe+Sn collisions, thanks to a simulation based on experimental data [12] in which a quantal temperature was calculated from the momentum fluctuations of protons present at freeze-out [13]. Pressure and volume-constrained caloric curves could be built and the expected behaviours were observed: a backbending for selected ranges of pressure and a monotonous increase at constant average volume [14] (see fig. 1).

### 3. – First results with isospin degree of freedom

In this section we will briefly review some first studies on phase transition signals with the introduction of the isospin variable that were experimentally observed in the past years.

**3'1. The caloric curves.** – A few experiments studied the effect of isospin on caloric curves, considering semi-peripheral collisions. Sfenti *et al.* for 600  $A$  MeV ( $^{124}\text{Sn}$ ,  $^{124}\text{La}$ ,  $^{107}\text{Sn}$ ) + Sn [15] and Wuenschel *et al.* for 35  $A$  MeV  $^{78}\text{Kr}$  +  $^{58}\text{Ni}$ ,  $^{86}\text{Kr}$  +  $^{64}\text{Ni}$  [16] found a small isospin effect, with slightly higher temperatures for the neutron-richer systems; conversely McIntosh *et al.*, for light quasi-projectiles of known  $A$  and  $Z$  formed in 35  $A$  MeV  $^{70}\text{Zn}$  +  $^{70}\text{Zn}$ ,  $^{64}\text{Zn}$  +  $^{64}\text{Zn}$ ,  $^{64}\text{Ni}$  +  $^{64}\text{Ni}$  observed measurable effects, with lower temperatures for neutron-richer nuclei [17]. Note that, unlike the ensemble of caloric curves presented in [18], none of those derived in [15–17] exhibits a plateau. In [17] the temperature linearly increases with energy between 2 and 8  $A$  MeV, reaching 12 MeV at  $E^* = 8 A$  MeV, well above the empirical value of  $T_{lim}$  for light nuclei estimated in [18].

On the theoretical side, the SMM model, as well as calculations considering a nucleus in equilibrium with its vapor, predict an increase of  $T_{lim}$  with isospin [19, 20], whereas in calculations dealing with isolated mononuclei, without surrounding vapor, the reverse trend is obtained [21]. In all cases the temperature variation with isospin is small.

**3'2. Phase transition and free energy.** – A new signature of first-order phase transition was experimentally investigated using the Landau free-energy approach [22]. Quasi-projectiles (QP) formed in 35  $A$  MeV  $^{64}\text{Zn}$  +  $^{64}\text{Zn}$ ,  $^{70}\text{Zn}$  +  $^{70}\text{Zn}$  and  $^{64}\text{Ni}$  +  $^{64}\text{Ni}$  were reconstructed and data sorted in different QP asymmetry ( $m_s = (N_s - Z_s)/A_s$ ) and excitation energy bins in the range 3–9 MeV per nucleon. According to the modified Fisher model to take into account finite-size effects, the free energy per nucleon of a fragment of mass  $A$  normalized to the temperature of the QP,  $F/T$ , can be derived from the fragment yield  $Y = y_0 A^{-\tau} e^{(-F/T)A}$ ;  $y_0$  is a constant and  $\tau$  is a critical exponent. In the Landau approach the free energy of a first-order phase transition is extended in a power series (sixth order) in the order parameter  $m = (N_f - Z_f)/A_f$ ;  $N_f$ ,  $Z_f$  and  $A_f$  are the neutron, proton and mass numbers of the fragment respectively. More details can be found in [22]. In fig. 2  $F/T$  values as a function of  $m$  are displayed for a QP excitation energy of 6.5 MeV per nucleon and for different asymmetry ( $m_s$ ) bins of the QP (different panels). Full lines correspond to the true Landau fit with the appearance of three minima, which is the signature of a first-order phase transition. Dashed lines correspond to single phase systems.

### 4. – Dynamics of the transition: spinodal instabilities or not?

In infinite nuclear matter the signature of spinodal instabilities is the formation of equal-sized fragments. The most unstable modes correspond to wavelengths lying around

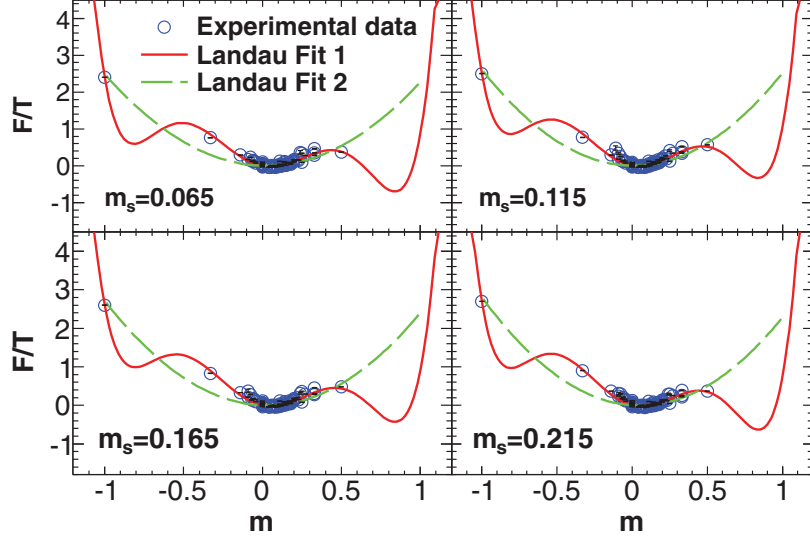


Fig. 2. –  $F/T$  as a function of fragment neutron-proton asymmetry  $m$  for an excitation energy of 6.5 MeV per nucleon of the QP. Different panels correspond to different neutron-proton asymmetry ( $m_s$ ) bins of the QP. Full lines are fits to the data using the complete Landau free energy (first-order phase transition) and dashed lines are fits which refer to single phase systems. Statistical errors are smaller than the points. From [22].

$\lambda \approx 10$  fm and the associated characteristic times are almost identical, around 30–50 fm/c, depending on density ( $\rho_0/2$ – $\rho_0/8$ ) and temperature (0–9 MeV) [1]. A direct consequence of the dispersion relation is the production of “primitive” fragments with size  $\lambda/2 \approx 5$  fm which correspond to  $Z \approx 8$ . However this simple picture is rather academic. A more realistic picture can be obtained from semiclassical calculations of collisions. Figure 3 shows such results for recent calculations for collisions between  $^{136}\text{Xe}$  and  $^{124}\text{Sn}$  at 32 A MeV [23] for central collisions and their evolution with time. In such simulations (BLOB) fluctuations are introduced in full phase space from inducing nucleon-nucleon collisions [24].

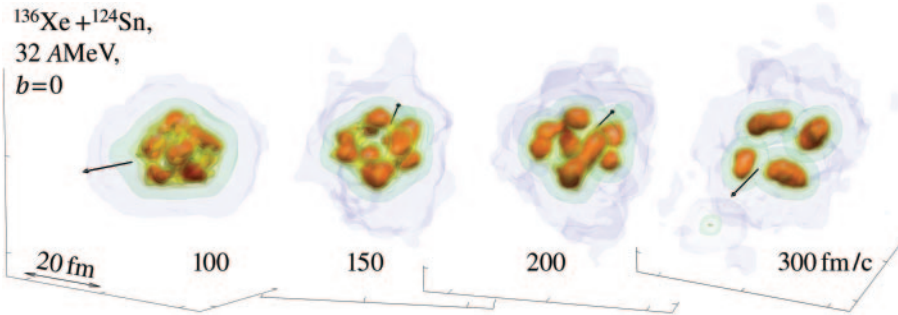


Fig. 3. – BLOB calculation for central  $^{136}\text{Xe} + ^{124}\text{Sn}$  collisions at 32 A MeV. Multifragmentation occurs with the spinodal pattern at 150 fm/c followed by a partial coalescence at later time. For better visibility, axis is modified for each time; arrows indicate the reaction axis. From [23].

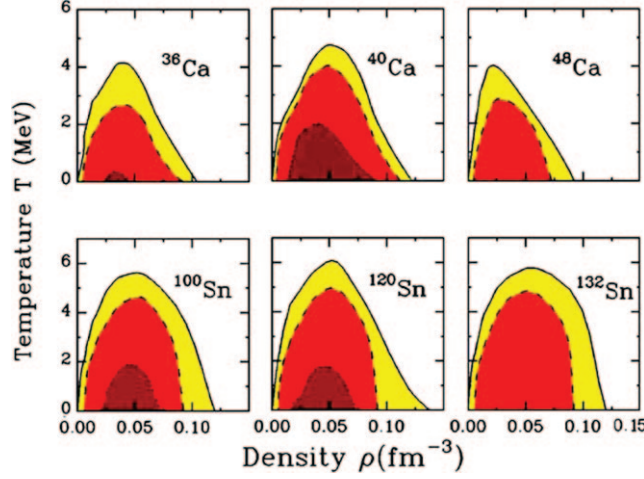


Fig. 4. – Border of the instability region. Boundaries of the instability region (solid lines) associated with  $L = 3$  collective modes in Ca and Sn isotopes. Phase points having the same growth time equal to either 100 fm/c (dashed) or 50 fm/c (dots) are also delineated. From [6].

One notes that despite finite-size effects (equally probable modes with beating) a large number of “primitive” fragments formed at 150 fm/c (around three times the characteristic time) are of comparable sizes in the region from Ne to O. Then coalescence occurs, which largely destroys the “primitive” composition and which well confirms that the final extra production of equal-sized fragments is a fossil signature. It is the reason why such signature is difficult to observe if the spinodal decomposition occurs.

As said in the introduction, a definitive conclusion concerning the dynamics of the transition was not obtained experimentally in relation with a too low confidence level (3–4  $\sigma$ ) for the extra production of equal-sized fragment partitions [3, 4]. Work is in progress in the INDRA Collaboration to give a final conclusion from experiments realized with much higher statistics. Various reactions have been used,  $^{124,136}\text{Xe} + ^{112,124}\text{Sn}$  at 32 and 45 A MeV, to produce quasi-fusion (QF) systems. One can also expect possible information related to the influence of isospin on spinodal instabilities from QF events formed from extreme reactions (difference of twenty four neutrons).

**4.1. Spinodal region and isospin degree of freedom.** – First of all, asymmetric nuclear matter at subsaturation densities is shown to present only one type of instability, which means a unique spinodal region [25]. The associated order parameter is dominated by the isoscalar density which implies a transition of the liquid-gas type. The spinodal zone is also predicted to shrink for increasing isospin asymmetry, reducing both the critical density and temperature [5]. For finite-size systems like nuclei the direct consequences are the following: heavier systems have a larger instability region than the lighter ones and more asymmetric systems/nuclei are less unstable (see fig. 4), which means a reduced effective spinodal zone compared to symmetric systems [6]. If spinodal instabilities are at the origin of the phase transition, any change of the spinodal region in the phase diagram should affect the signals previously discussed.

**4.2. Spinodal instabilities vs. equilibrium as dynamics of the transition.** – Considering the asymmetric nuclear matter liquid-gas phase transition analyzed in a mean-field

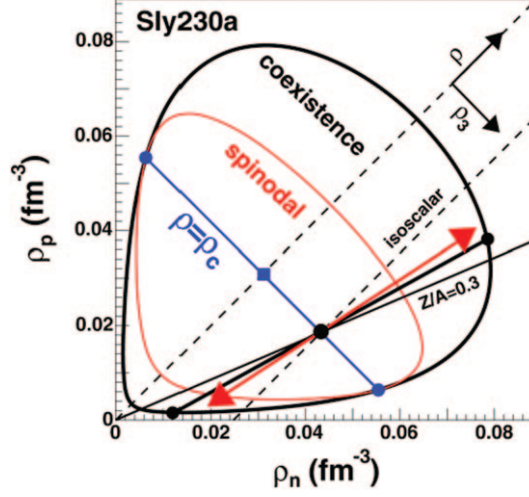


Fig. 5. – Coexistence and spinodal regions in the proton-neutron density plane at  $T = 10$  MeV. Illustration of phase separation inside the instability region for matter with a proton fraction  $Z/A = 0.3$  (see text). From [7].

approach, two different mechanisms of phase separation (dynamics of the transition) can be compared: equilibrium and spinodal decomposition [7]. The isospin properties of the phases are deduced from the free-energy curvature, which contains information on the average isospin of the phases and on the system fluctuations. The results are illustrated in fig. 5 for neutron-rich matter with  $Z/A = 0.3$  and a temperature  $T$  of 10 MeV. If equilibrium is the origin of phase separation, the system will undergo separation according to Gibbs construction. The two phases, represented as black dots on the coexistence border do not belong to the line of constant proton fraction ( $Z/A = 0.3$ ). The liquid fraction is closer to symmetric matter than the gas phase. It is a consequence of the symmetry energy minimization in the dense phase. This unequal repartition of isospin between the two phases is the well-known phenomenon of isospin fractionation. One can now study isospin fractionation if phase separation is driven by spinodal instabilities. This is the spinodal decomposition and the local properties of the constrained entropy curvature determine the development into phase separation. The double arrow in fig. 5 shows the results; the spinodal decomposition leads to a more pronounced fractionation than equilibrium, the dense phase getting closer to the symmetric matter.

This fact can be a possible new signature of the dynamics of the phase transition. However it appears as a very challenging problem. For experimentalists large  $Z/A$  values are required to have enough sensitivity. A robust reconstruction of primary fragments is also mandatory. Moreover future  $A$  and  $Z$  identification arrays, like for example FAZIA, are absolutely needed for such studies [26,27]. On the theoretical side more realistic calculations involving collisions between nuclei are essential.

## 5. – Conclusions

The presence of a first-order phase transition for hot nuclei (or nuclear systems) seems well established and is not contradicted by recent results taking into account the isospin degree of freedom. A key point still remains: the origin of the dynamics of the

transition which is unknown. If spinodal decomposition occurs, it is confirmed by recent improved realistic calculations involving collisions that the extra production of equal-sized fragments is a fossil signature and it can be difficult to experimentally evidence such a signal. Works are in progress with high statistics to possibly give a final answer. The introduction of the isospin degree of freedom into the game opens possibilities for new signatures of spinodal instabilities. A direct one is the reduction of the effective spinodal region for asymmetric systems. A second more indirect one concerns isospin fractionation. The spinodal decomposition leads to a more pronounced fractionation than equilibrium, which is the alternative for the dynamics of the transition. However the latter signature is very difficult to quantitatively obtain at both levels experimental and theoretical.

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